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Evaporation of Strange Matter (and Similar Condensed Phases) at High Temperatures

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(NASA-CR-186786) EVAPORATION OF STRANGE MATTER (AND SIMILAR CONDENSED PHASES) AT HIGH TEMPERATURES (Fermi National Accelerator Lab.) 6 p

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Abstract

Strange matter is a form of quark matter that has been conjectured to be stable at zero temperature. If heated to a temperature $T \geq 2MeV$, a strange matter lump evaporates nucleons from its surface. We show that at higher temperatures ($T \geq 20MeV$), strange matter ***boils***, with bubbles of hadronic gas forming and growing throughout the interior. Strange matter, or any other phase which resembles strange matter, could not have survived this process in the early universe.

Strange matter is postulated to be the true ground state of QCD[1]. It consists of roughly equal numbers of up, down and strange quarks confined in a quark phase. Calculations based on the bag model have shown that this speculation is plausible.[2] The potential consequences of this hypothesis for astrophysics have been reviewed in Ref. 3.

It was originally proposed that much of the baryon number of the universe condensed into lumps of strange matter during the quark-hadron phase transition[1]. Subsequently, it was shown that evaporation of these objects at temperatures $T \leq 50 MeV$ was extremely efficient[4]. The strong conclusion was reached that only objects which had baryon number $\geq 10^{52}$, which is $\sim 10^{3}$ times the mean baryon number in the horizon at the epoch of formation, could survive this process. It appeared that strange matter had been eliminated as a constituent of the cosmic dark matter (unless some acausal formation process could be invoked).

This conclusion was criticized for its inadequate treatment of flavor equilibration near the surface of the evaporating lump[5]. Since the emitted hadrons are primarily neutrons and some protons, the remaining quark matter just inside the lump becomes deficient in down quarks and too rich in strange quarks. A new evaporation rate was calculated which took into account flavor disequilibration and it was concluded that strange lumps with baryon number as low as $\sim 10^{46}$ could survive evaporation[5]. This number is greater than that originally proposed,[1] but well within the causality limit (10^{49}).

We describe here a process that most probably is more important than surface evaporation and which would lead to the dissolution of lumps of strange matter with baryon number as high as 10^{43}. For temperatures $T \geq 0.1I$, where I is the binding energy of the neutron in strange matter ($I \sim 20 MeV$), the hadron gas is thermodynamically favored, since it has higher entropy and hence lower free energy than strange matter. Bubbles of hadronic gas spontaneously nucleate throughout the volume of the strange matter lump. Each bubble grows, and the baryon number of the quark phase is emptied into the growing bubbles.[6] In this case, flavor disequilibration is not important as long as the total surface area of the hadronic bubbles is much larger than the surface area of the strange matter lump.

The rate at which bubbles are formed may be estimated using classical nucleation theory.[7] The thermodynamic work expended to create a small bubble of true vacuum which contains hadrons is:

$$W = \frac{4\pi}{3} r^3 (P_e - P_i) + 4\pi\sigma r^2 \quad , \qquad (1)$$

where r is the radius of the bubble, P_e is the pressure in the strange matter (which is equal to the mean pressure in the universe), P_i the pressure inside the bubble, and σ the surface tension. The nucleation rate is determined by the abundance of "critical bubbles" for which W is maximized; these bubbles have radius $r_c = 2\sigma/(P_i - P_e)$, yielding

$$W_c = \frac{16\pi}{3} \frac{\sigma^3}{(P_i - P_e)^2} \quad . \qquad (2)$$

The rate at which critical bubbles appear is then

$$p(T, \mu) \sim \epsilon^4 exp(-W_c/T) \qquad (3)$$

where the explicit dependence of the nucleation rate on T and the baryon chemical potential inside strange matter (μ) is indicated. The quantity ϵ is a "characteristic energy" in the kinetics; the precise magnitude of ϵ is unimportant, but we expect $\epsilon \geq T$.

The external pressure P_e is contributed entirely by the thermal spectrum of light particles (e, ν, γ). The internal pressure contains an identical contribution due to these particles plus that due to neutrons and protons. The pressure difference is

$$P_i - P_e = (\frac{2}{\pi^3})^{1/2} m^{3/2} T^{5/2} exp(\frac{\mu - m}{T}). \qquad (4)$$

where m is the mass of the nucleon.[8] It is easy to see that $I = m - \mu$, whence

$$\frac{W_c}{T} = \frac{8\pi^4}{3} \frac{\sigma^3}{m^3 T^6} exp(\frac{2I}{T}) \quad . \qquad (5)$$

The rate at which bubbles of hadron gas spontaneously appear is given by equation (3) and (5). To obtain the characteristic number density of bubbles which form at temperature T, this rate should be multiplied by the duration of the epoch (of order the expansion time) $\sim 0.1 M_P/T^2$ (where M_P is the Planck mass). Taking $\epsilon \sim T$ we obtain a conservative estimate of the number density of bubbles, $n_s \sim 0.1 M_P T^2 exp(-\frac{W_c}{T})$.

The above analysis is only meaningful if $n_s << n_B$, where n_B is the baryon number density in strange matter ($n_B = (125MeV)^3$). This requires $W_c/T \geq 43$ (at $T = 100MeV$). In the event that this inequality is not satisfied, the nucleation is so efficient that phases which are far from thermodynamic equilibrium would not appear in the first place: strange matter would not be formed. This conclusion was reached, for rather different reasons, by Applegate and Hogan.[9]

On the other hand, if $W_c/T \geq 85$ the number of nucleation sites becomes so small that the total surface area of the bubbles is smaller than the bounding surface area of the lump, for lumps with baryon number in the interesting range $10^{46} - 10^{49}$. In this limit, flavor disequilibration would be important and the boiling less efficient. The most important physical uncertainty in the evaluation of W_c/T is the magnitude of σ. If we impose $W_c/T \geq 85$, it would correspond to $\sigma \geq (107MeV)^3$ if $T = 50MeV$, or to $\sigma \geq (178MeV)^3$ if $T = 100MeV$. Neither of these possibilities is excludable at present, though both are significantly higher than one would expect ($\sigma \leq (70MeV)^3$).[2] Since the expressions should be evaluated at the highest temperature encountered by the strange matter, we choose here the more stringent limit on σ.

Thus, nuggets of strange matter might have survived dissolution into hadrons in the early universe only if their baryon number exceeded 10^{46} and if the surface tension $\sigma \geq (178MeV)^3$. Since the latter requirement seems implausible, we conclude that any nuggets of strange matter were dissolved into hadrons. A similar fate would have faced any other objects which resembles strange matter; an example of such an object would be six-flavor quark matter.[10]

Finally we note that these considerations have important consequences for models of gamma-ray bursts which involve collisions between lumps of strange matter and strange stars.[11] Such collisions heat the material to $T \sim 40MeV$. Unless the surface tension is very high (as described above), large numbers of bubbles of hadron gas will form inside the strange matter, and will grow until the system reaches equilibrium at $T \sim 2MeV(= 0.1I)$. These bubbles will rise to the surface, and most of the energy will be released in the form of small bubbles of hadronic gas. This will have as yet unknown consequences for the spectrum of the emitted photons.

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